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January 14, 1955

Mr. Robert D. Nininger, Acting Assistant Director  
Division of Raw Materials  
U. S. Atomic Energy Commission  
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Washington 25, D. C.

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Sincerely yours,

*John H. Eric*  
for W. H. Bradley  
Chief Geologist

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UNITED STATES DEPARTMENT OF THE INTERIOR  
GEOLOGICAL SURVEY

LITHIUM RESOURCES OF NORTH AMERICA

By

James J. Norton  
and  
Dorothy McKenney Schlegel

October 1954

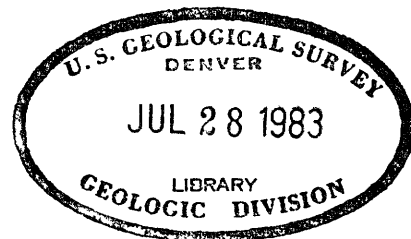
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## LITHIUM RESOURCES OF NORTH AMERICA

By James J. Norton and Dorothy McKenney Schlegel

## ABSTRACT

The United States and Canada have more than ample lithium resources to support the expanding lithium mining industry. The largest reserves are in the tin-spodumene belt of the Carolinas, which was first developed during World War II and is now the largest source of lithium in the world. Prior to World War II, deposits in South Dakota were the chief source of lithium minerals, and these deposits still contain significant reserves. In California lithium has been produced from Searles Lake brines since 1938, and during earlier years lepidolite was mined in the Pala district. Other states containing lithium deposits are New Mexico, Colorado, Wyoming, Connecticut, Maine, and Massachusetts. Canadian resources still are being developed. Significant deposits have not been reported elsewhere in North America.

The earth's crust contains about 0.006 percent lithium, or about 0.013 percent  $\text{Li}_2\text{O}$ . This is close to the grade of the Searles Lake brines, which contain 0.015 percent  $\text{Li}_2\text{O}$ . Pegmatite deposits, on the other hand, must contain 1.0 percent  $\text{Li}_2\text{O}$  in order to be mined profitably.

The most abundant lithium mineral occurring in pegmatites is spodumene. Other minerals include amblygonite, lepidolite, petalite, and triphylite-lithiophilite. These most commonly occur in mineral assemblages that are characteristic of inner zones and replacement bodies of pegmatites.

Indicated reserves in the pegmatites of the United States are 5,000,000 units of  $\text{Li}_2\text{O}$ . By far the greatest reserves in pegmatites are in the Carolinas. Reserves in Searles Lake, Calif., may amount to 9,000,000 units. Inferred reserves in the United States and Canada are about 125,000,000 units of  $\text{Li}_2\text{O}$ . In contrast to these figures, domestic consumption in 1953 was about 250,000 units.

## INTRODUCTION

Lithium mining has been one of the most rapidly expanding mineral industries in the decade following World War II. In all but a few of the years prior to 1939, the gross value of all lithium minerals consumed annually by the United States was less than \$50,000; by 1953, however, the value approached \$2,000,000. This rapid expansion makes a study of our lithium resource position desirable, in order to estimate the level of production that can be sustained by known and readily predictable reserves.

The purpose of this report is to compile and analyze all available data on lithium resources. Much of this information was obtained during work by many U. S. Geological Survey geologists in the principal domestic pegmatite districts between 1939 and 1953. Additional data have been found in many published and unpublished reports. Information concerning Canadian deposits has been obtained from the available published reports. Significant lithium deposits are not known elsewhere in North America.

This report has been greatly improved by suggestions from various members of the Geological Survey, especially Michael Fleischer, who called attention to published reports and analytical data that would not have been found without his aid.

### Uses and properties of lithium

Lithium is the third element of the periodic table. The atomic weight is 6.940, which makes it the lightest of all metals. Its chemical properties place it in the alkali metal group with sodium, potassium, rubidium, and cesium. Lithium is univalent.

Lithium minerals are ordinarily processed to make lithium carbonate and other lithium compounds used in industry, but lepidolite has been extensively used as a direct ingredient in glass making. Before World War I lithium compounds were used chiefly as ingredients in mineral waters and effervescing lithia tablets. The next important use was in alkaline storage batteries; this use probably in large part accounted for the increase in production during World War I. Subsequently the use of lithium compounds in ceramics became important. The hygroscopic nature of lithium chloride is the basis of use in industrial drying and air-conditioning.

Increased demand during World War II was largely caused by the use of lithium hydride as a hydrogen carrier to inflate certain types of naval and air force rescue equipment.

The transient uses during World War II were succeeded by more permanent uses that created a strong market leading to the great expansion of the industry in the years following 1948. The greatest demand was in greases, ceramics, and air-conditioning. Lithium soaps are used in the manufacture of multi-purpose greases that can withstand extreme temperatures. Alkaline storage batteries and pharmaceutical uses also continue to be important. Lithium is used as a flux in aluminum welding and brazing. It has important metallurgical uses, especially for degassing and purifying other metals and alloys. Many other uses of lithium have been reported.

#### History of lithium mining and production

The first recorded production of lithium in the United States consisted of an estimated 30 tons of lithium minerals mined in 1889 (table 1), but the source of this material is not recorded. Lepidolite was mined as early as 1892 at the Stewart mine, Pala, Calif. (Jahns and Wright, 1951, p. 59). Spodumene was first obtained in 1898 at the Etta mine, Keystone, S. Dak. (Connolly and O'Harra, 1929, p. 240). The year 1898 is ordinarily regarded as marking the start of lithium mining in the United States (Schaller, 1919, p. 7).

Amblygonite was first obtained as a byproduct of lepidolite mining at the Stewart mine in 1902 (Jahns and Wright, 1951, p. 51, table 5), and it was produced at the Tin Queen mine, Hill City, S. Dak., about 1905 (Hess, 1911, p. 652). Amblygonite production from South Dakota deposits rapidly became dominant in the industry and remained so until 1917.

Lithium production figures for the years prior to 1917 are inadequate (table 1), but 1901-1903 was probably the only period in which annual production exceeded 1,000 tons of lithium minerals or had a gross value of more than \$20,000.

Production increased during World War I, and reached a maximum of 11,696 tons in 1920. This was the period of greatest activity at the Stewart mine, Pala, Calif.; it was also one of the more productive periods in the history of the Etta mine, Keystone, S. Dak.

Table 1.--Lithium mineral production of the United States 1/

Year	South Dakota 2/			California		Other States			Units of lithia 3/
	Total	Spodumene	Amblygonite	Tons	Value	Lepidolite	Tons	Value	
1889									
1890									
1891									
1892									
1893									
1894									
1895									
1896									
1897									
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1948									
1949									
1950									
1951									
1952									
1953									
Totals									

1/ Abbreviations are: est. - estimated or approximate; N.A. - not available; ? - possibly some production, but figures not obtainable.  
 2/ Figures through 1944 were published in Page 1, R., and others, 1953, p. 3, table 1. These figures were obtained chiefly from Lincoln, F. C., U. S. Bur. Mines unpublished report, but a few of the figures were revised by L. H. Page on the basis of operation records.  
 3/ The figures for 1931-1934 are for the production of the United States, and for 1935-1944 are for the production of the United States and Canada.  
 4/ From James and Wright, 1951, p. 51, table 5.  
 5/ Most of the estimates of the number of units of lithia produced probably have errors of less than 2.0 percent. A unit is 1 percent per ton, or 20 lbs. of contained Li<sub>2</sub>O.  
 6/ The symbol \* indicates years in which discrepancies between figures for total U. S. production and the data for individual States are not readily explainable.

7/ Production of only 21 tons from this district reported in Mineral Resources of the U. S., 1905.  
 8/ Includes 100 tons of tripylite valued at \$3,000.  
 9/ Includes production of Becher Lake from 1935-1936.  
 10/ Includes production of Becher Lake from 1937-1938.  
 11/ Includes production of Becher Lake from 1939-1940.  
 12/ May include a small quantity of amblygonite.  
 13/ From J. C. Arundale, U. S. Bureau of Mines.  
 14/ One operator may have produced as much as 6,000 tons not included in this total.

Production dropped to 1,833 tons in 1921, and then gradually increased during the 1920's until it reached 4,600 tons in 1928. During these years the chief source was the Harding mine, Taos County, N. Mex., where spodumene-lepidolite concentrates were produced; but spodumene from the Etta mine and lepidolite from the Stewart mine were also important.

Lithium mines were inactive in the early 1930's, but production was resumed in South Dakota during the latter half of the decade. As in the past, the Maywood Chemical Co. mined spodumene at the Etta mine. Lepidolite production first became significant in the Black Hills in 1937, when it was mined from the Bob Ingersoll No. 1 pegmatite, near Keystone. The American Potash and Chemical Corporation began the production of dilithium sodium phosphate at Searles Lake, Calif., in 1938.

Lithium mining increased greatly during World War II, and reached a peak production of 84,800 units of lithia in 1944. This increase in production was possible largely because of the introduction of modern mineral dressing techniques, which permitted exploitation of deposits of fine-grained lithium minerals that could not be concentrated by hand-cobbing methods used previously. The Solvay Process Co. built the largest of these mills at Kings Mountain, N. C. Spodumene was also milled at Tinton, S. Dak. Lepidolite was milled in South Dakota and Colorado.

Annual production from 1945 through 1948 averaged about 27,000 units. \_\_/ In succeeding years pro-

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\_\_/ A unit consists of 1 percent  $\text{Li}_2\text{O}$  per ton of ore.

---

duction increased until in 1952 it exceeded 100,000 units, and at the present rate of development should soon reach 200,000 units. Domestic consumption in 1953 was about 250,000 units. A major producer has been the Foote Mineral Co., which purchased the Solvay properties in North Carolina in 1951 and began mining and milling spodumene soon thereafter. Searles Lake has continued to be a major source.

From 1948 to 1950 the Lithium Corporation of America used a sink-float process to concentrate spodumene from the Edison mine near Keystone, S. Dak. In 1952 this company completed a spodumene flotation plant at Hill City, S. Dak., to process ore from the nearby Mateen pegmatite and from the Beecher No. 2 pegmatite, about 15 miles to the south. The Black Hills Tin Co. resumed mining at Tinton, but work came to a halt when the mill burned in November 1953. The Etta mine and several smaller operations also contributed to the Black Hills production.

Recorded production figures for South Dakota, California, other states, and the entire United States through 1953 are shown on table 1. The national totals for many of these years are not consistent with the figures for the various states, and sufficient data to resolve the discrepancies were not obtainable. For example, the figures for early production in South Dakota may have significant errors. Schaller (1937, p. 430) reported that before 1935 South Dakota had produced 26,000 tons of lithium minerals; table 1, however, shows only 18,600 tons.

#### Imports and exports

Import and export figures for lithium minerals are not reported separately, and complete data are not available. Prior to World War II the United States was a net exporter, chiefly to Germany. Since World War II, there have been large imports of lepidolite from Southwest Africa and petalite from Southern Rhodesia. Other countries have significant lithium deposits, and in the future production from these deposits may increase the supply of lithium minerals on the world market.

#### Prices

The U. S. Bureau of Mines Minerals Yearbook for 1950 (Lamb and others, 1953, p. 1350) quotes the following prices for lithium minerals at the mine:

Spodumene, \$6 to \$8 per unit consisting of 1 percent  $\text{Li}_2\text{O}$  per short ton of ore.

Lepidolite, 4 percent  $\text{Li}_2\text{O}$ , \$80 per short ton.

Amblygonite, \$110 per short ton.

Dilithium sodium phosphate, \$9 per unit.

Quoted prices were essentially the same at the end of 1953.

Nearly all material that is sold on the open market as raw concentrates of lithium minerals is imported from foreign sources. Concentrates from domestic sources are ordinarily processed by the same companies that do the mining, and the lithium is not sold until it is in the form of lithium compounds or lithium metal. The only exception is lepidolite used in glass-making, which may be sold directly to the consumer.

## GEOLOGY OF LITHIUM

### Distribution of lithium

Available data indicate that the earth's crust contains about 0.006 percent lithium (Fleischer, 1953, p. 4, table 2). Rankama and Sahama (1950, p. 422-428) show that igneous rocks contain an average of about 0.0065 percent lithium, and sedimentary rocks contain somewhat less.

The lithium content of sea water has been reported as 0.1 part per million (Thomas and Thompson, 1933, p. 548). Rankama and Sahama (1950, p. 295, 428) show that only 0.3 percent of the lithium supplied to sea water remains in solution; they presume that the remaining 99.7 percent goes chiefly into clays. Thus, unrecognized lithium concentrations may be present in sedimentary rocks.

Known lithium minerals, however, occur almost entirely in pegmatites. The only other source of lithium is at Searles Lake, Calif., where the lithium is in solution in brine extracted from evaporite beds. The clay mineral hectorite is the only mineral of sedimentary rocks known to contain enough lithium to be of possible commercial interest.

The small lithium content of igneous and metamorphic rocks is distributed among several minerals, especially biotite, pyroxene, and amphibole. Possibly lithium is more common than available analyses indicate. Certainly, however, it is very rare for any of these minerals to have as much as 1 percent  $\text{Li}_2\text{O}$ , or for rocks containing these minerals to have as much as 0.1 percent  $\text{Li}_2\text{O}$ . These occurrences have no commercial significance.

### Mineralogy of lithium ores and concentrates

#### Pegmatite lithium minerals

The chief lithium minerals mined from pegmatites of North America are spodumene, amblygonite, and lepidolite. Zinnwaldite, other lithium micas, and triphylite-lithiophyllite have been used only in small quantities, but may become more important (table 2). Petalite is an important product of foreign deposits.

Table 2. --Composition of the principal lithium minerals of pegmatites

Mineral	Formula	Theoretical $\text{Li}_2\text{O}$ content (percent)	$\text{Li}_2\text{O}$ content of marketed concentrates (percent)
Spodumene	$\text{LiAl Si}_2\text{O}_6$	8.03	4-7.5
Amblygonite-montebrazite-natromontebrazite series	$(\text{Li, Na}) \text{Al} (\text{PO}_4) (\text{F, OH})$ End member montebrazite with maximum lithium content is $\text{LiAl} (\text{PO}_4) (\text{OH})$	0-10.24 <u>1/</u>	8-9
Lepidolite, lithium muscovite, zinnwaldite, and other lithium micas	$\text{K}(\text{Li, Al, Fe})_3\text{Si}_3\text{-4 O}_{10} (\text{OH, F})_2$ End member polyolithionite or lepidolite with maximum lithium content is $\text{K Li}_2 \text{Al Si}_4 \text{O}_{10} (\text{OH})_2$	0-7.74	2.5-5
Petalite	$\text{LiAl Si}_4\text{O}_{10}$	4.88	3-4
Triphylite-lithiophilite series	$\text{Li} (\text{Fe, Mn}) \text{PO}_4$	9.47-9.53	Rarely marketed

1/ Palache and others (1951, p. 825) record only one analysis in which the  $\text{Li}_2\text{O}$  content is less than 6 percent. This is natromontebrazite or fremontite containing 3.21 percent  $\text{Li}_2\text{O}$ , reported by Schaller, 1911, p. 48.

Spodumene is a monoclinic member of the pyroxene group of minerals. The simplified formula for spodumene is  $\text{LiAlSi}_2\text{O}_6$ , indicating a theoretical content of 8.03 percent  $\text{Li}_2\text{O}$ . Many analyses show Na and K, which presumably substitute for Li, and also Fe, Mg, and Ca. (For examples, see Dana, 1892, p. 367.) Spodumene containing more than 7.5 percent  $\text{Li}_2\text{O}$  is rare.

Spodumene is ordinarily white to light gray in color, but gem varieties are green (hiddenite) or lilac-colored (kunzite). The luster is vitreous on fractured surfaces and pearly to silky on cleavages. Crystals characteristically are elongate blades having a flat cross-section. Rounded and square cross-sections are also common. Anhedral spodumene is rare. A spodumene crystal as much as 47 feet long has been reported (Schaller, 1916, p. 138), but deposits are known in which nearly all grains are less than a quarter of an inch long (Page and others, 1953, p. 204). Crystals break readily along cleavage surfaces to form splintery laths.

A distinctive characteristic of spodumene is pseudomorphic replacement by many other minerals. Spodumene may be so thoroughly replaced by micaceous and clay minerals that the lithia content is less than 0.1 percent, yet the cleavage of spodumene may still be preserved (Schwartz and Leonard, 1926, p. 257-264; Staatz, M. H., written communication). The so-called "altered", "soft", or "rotten" spodumene is gray, green, or pink. Many standard mineralogic texts (for example, Dana, 1932, p. 564) describe the alteration of spodumene first to a sodium-rich product consisting of eucryptite ( $\text{LiAlSiO}_4$ ) and albite, and subsequently to potassium-rich products in which muscovite takes the place of eucryptite. These statements, however, are based almost entirely on studies of the Branchville, Conn., pegmatite; they may have wider application, but knowledge in this regard is incomplete.

Pseudomorphic replacement of spodumene by coarser pegmatite minerals has been recognized by Norton and Page in the Hugo pegmatite and by Sheridan, written communication, in the Peerless pegmatite near Keystone, S. Dak. The spodumene parentage can be recognized by the characteristic bladed shape of the aggregates and by cleavelandite sheaths that surround both the pseudomorphs and unreplaced spodumene crystals. The minerals replacing spodumene are quartz, albite, perthite, muscovite, beryl, amblygonite, apatite, and tourmaline.

A thorough study of the alteration products of spodumene, using modern mineralogic techniques, has not been made. An investigation of this sort might obtain information useful in research on spodumene beneficiation.

Amblygonite ( $\text{Li, Na Al (PO}_4\text{) (F, OH)}$ ) is the common name of a phosphate series in which hydroxyl-rich material is sometimes called montebrasite and the fluorine end of the series is amblygonite in the strict sense. Sodic montebrasite containing little lithia has been called natromontebrasite (Palache and others, 1951, p. 823-825), natramblygonite (Schaller, 1911, p. 48), and fremontite (Schaller, 1914, p. 356, and 1916, p. 141). Schaller (1911, p. 48) reported that the type specimen of this material contained 3.21 percent  $\text{Li}_2\text{O}$  and 11.23 percent  $\text{Na}_2\text{O}$ . Actually, however, material of this sort is so exceedingly rare that for all practical purposes the amblygonite series ranges from 6.7 to 9.65 percent  $\text{Li}_2\text{O}$  (Palache and others, 1951, p. 825).

Amblygonite is ordinarily milky white to gray in color. The luster is pearly on the principal cleavage, but otherwise vitreous. Amblygonite occurs most commonly as rounded or ellipsoidal masses that commonly exceed 5 feet in diameter. The outer surface of many amblygonite masses is coated with a characteristic chalky covering that consists of micaceous and clay minerals.

The name lepidolite is applied in the lithium mining industry to a widely varied group of lithium micas. Marketable lepidolite ordinarily must contain 3 to 4 percent  $\text{Li}_2\text{O}$ . Nearly all such lepidolite is pink, lilac, or violet-gray in color. Gray and rose-colored micas containing less lithia are sometimes called lepidolite. All varieties occur most commonly as fine-grained aggregates associated with albite and other pegmatite minerals.

Knowledge of the mineralogy of lepidolite and its relatives has been greatly enlarged in recent years as a result of work by Levinson (1953), Winchell (1942), Hendricks and Jefferson (1939), and Stevens (1938). These authors show that the lithium micas belong to a complex series with various structures that fit in the hexagonal, monoclinic, and triclinic systems. The many members include: muscovite, lithium muscovite, polyolithionite (lithium-rich mica), protolithionite and zinnwaldite (iron-rich micas), biotite, and taeniolite (magnesium-lithium mica). The simplest general formula for this series is  $\text{K (Li, Al, Fe)}_3 \text{Si}_{3-4} \text{O}_{10} (\text{OH, F})_2$ .

Levinson (1953) found a continuous gradation in composition between muscovite and lepidolite. Micas containing less than about 3.3 percent  $\text{Li}_2\text{O}$  have the structure of muscovite. Micas containing 3.4-4.0 percent  $\text{Li}_2\text{O}$  belong to three different structural varieties of lepidolite. The richest sample contained 7.26 percent  $\text{Li}_2\text{O}$ , and the theoretical maximum is 7.74 percent  $\text{Li}_2\text{O}$  (Stevens, 1938, p. 619-620).

These studies indicate that the lepidolite of commerce has a significant range of composition and structure. At the present time these differences have no practical importance, but in the future a knowledge of them may be of value in developing specialized uses of the various lithium-bearing micas.

Petalite ( $\text{Li Al Si}_4\text{O}_{10}$ ) occurs as white to gray masses. For many years petalite has been described in the literature as a source of lithium, but actually it was rarely used for this purpose until recently. Significant petalite deposits are unknown in North America, but petalite deposits elsewhere are economically important (Clark, J. D., 1950, p. 1068).

Pegmatites have a wide variety of phosphate minerals that contain lithium, iron, manganese, calcium, and other constituents. The principal minerals are in the triphylite-lithiophilite series, which has the formula  $\text{Li (Fe, Mn) PO}_4$ . Lithium can be replaced by sodium and calcium to form the less common hühnerkobelite series, and thus gradations from 0 to 9.55 percent lithia may occur (Palache and others, 1951, p. 664-670).

Triphylite-lithiophilite is bluish gray to brown in color, but ordinarily it is intimately associated with many alteration products that make the color grayish brown to nearly black. Triphylite-lithiophilite is also intergrown with other primary pegmatite minerals. Phosphate-rich aggregates form rounded masses ranging from a few inches to several feet in diameter. The mineralogy of such aggregates is difficult to study; these aggregates may contain many undescribed species of phosphate minerals.

The difficulty of using hand-cobbing methods to obtain a lithium-rich concentrate of consistent composition from aggregates of this sort doubtless is one of the main reasons why these minerals have rarely been mined. Triphylite-lithiophilite and its associated minerals have been found in and near minable deposits of other lithium minerals, and now that milling is widely used in the lithium mining industry, the triphylite-lithiophilite may also be produced. More study of the mineralogy of these minerals and their possible economic applications is needed.

Eucryptite ( $\text{LiAlSiO}_4$ ) has generally been considered a very rare mineral. For three-quarters of a century it was known only at Branchville, Conn., but recently it was found in Arizona (Adams, J. W., oral communication), New Mexico, and New Hampshire (Mrose, 1952, p. 1283). Still more recently it was found in a large petalite deposit at Bikita, Southern Rhodesia (Fleischer, Michael, oral communication, 1953). No data are available concerning the abundance of eucryptite in this deposit. Possibly eucryptite is more abundant in this and other pegmatites than heretofore supposed.

Cryolithionite ( $\text{Na}_3\text{Li}_3\text{Al}_2\text{F}_{12}$ ) has been described in cryolite deposits (Palache and others, 1951, p. 99-100). It is not known to occur in significant quantities anywhere in the world.

#### Non-pegmatite lithium minerals

One of the principal sources of lithium is Searles Lake, Calif., where the lithium is in solution in brines. No lithium minerals, however, have been described in saline deposits. The lithium in saline deposits may be a minor constituent of the major minerals, where it could occupy alkali positions in the lattices.

Hectorite is the only known lithium-bearing mineral of sedimentary rocks that is potentially important as a source of lithium, and it has been reported only at Hector, Calif. Hectorite is an end member of the montmorillonite group that is rich in magnesium, lacks aluminum, and contains about 1 percent lithia (Ross and Hendricks, 1945, p. 27, 35, 47). The formula is  $16\text{MgO} \cdot \text{Li}_2\text{O} \cdot 24\text{SiO}_2 \cdot 6(\text{F}, \text{H}_2\text{O}) \cdot (\text{Na}_2\text{O})$ . Lithium is an essential part of the crystal lattice and cannot be replaced by simple base exchange (Ross and Hendricks, 1945, p. 38).

#### Types of lithium deposits

Pegmatite deposits containing spodumene, amblygonite, and lepidolite are the chief sources of lithium, and were the only sources prior to 1938, when lithium production began at Searles Lake, Calif. (Mumford, 1949, p. 513). No North American deposits have been mined for petalite and no deposits

anywhere have been mined for lithium mica containing less than 2.5 percent  $\text{Li}_2\text{O}$ . Small quantities of triphylite-lithiophilite have been used as a lithium source, presumably only in experimental work. Searles Lake is the only other commercial source of lithium. Lithium has also been detected, however, in saline deposits, clays, and other sedimentary rocks, and also in hot springs.

### Lithium deposits in pegmatites

Nearly all lithium pegmatites mined in the United States and Canada are intrusive into metamorphic rocks. Lithium pegmatites large enough to be of commercial interest intrude igneous rocks in Quebec (Derry, 1950; Rowe, 1953 a & b).

Most pegmatites from which lithium minerals have been profitably extracted can be classified as well-segregated zoned or heterogeneous pegmatites. Many spodumene pegmatites, however, consist of essentially the same rock from wall to wall. Such pegmatites may have a fine-grained border zone or wall zone, and slight changes in mineralogy and texture may be recognizable within the pegmatite. Clear distinctions between pegmatite units may be difficult to find.

Lithium deposits occur with mineral assemblages that Cameron and others (1949, p. 59-70, tables 1-5) show are characteristic of inner units of pegmatites. Table 3 shows the principal lithium minerals and non-lithium minerals in the sequence of 11 assemblages described by Cameron and others. No pegmatite contains all of these assemblages, but those in any one pegmatite occur from the wall inward in the sequence given in the table. This sequence probably is also the order in which the units formed. Nearly all lithium deposits are in zones 5 through 8.

Table 3 shows that the mineralogy of lithium is very closely correlated with the mineralogy of the pegmatite units in which it occurs. The lithium phosphates, especially triphylite-lithiophilite, are most common in the first part of the sequence, where perthite and muscovite are common minerals. Amblygonite tends to be nearer the montebrasite or hydroxyl end of the series in outer units and nearer the fluorine end of the series in inner units of certain pegmatites of the Black Hills, S. Dak. (Norton and Page, Geology of the Hugo pegmatite, Keystone, S. Dak., in preparation). This relationship has not been demonstrated elsewhere.

Table 3. -- Distribution of the principal lithium minerals of pegmatites

Assemblage	Principal non-lithium minerals <u>1</u> /	Principal lithium minerals
1	Plagioclase, quartz, muscovite	Amblygonite (especially montebrasite(?))
2	Plagioclase, quartz	None
3	Quartz, perthite, plagioclase, muscovite	Triphylite-lithiophilite
4	Perthite, quartz	Triphylite-lithiophilite
5	Perthite, quartz, plagioclase	Amblygonite, spodumene
6	Plagioclase, quartz	Spodumene, petalite(?)
7	Quartz	Spodumene
8	Plagioclase, quartz	Lepidolite
9	Quartz, microcline	None
10	Microcline, plagioclase, quartz	Lithium muscovite
11	Quartz	None

1/ After Cameron and others, 1949, p. 68.

The richest spodumene-bearing units tend to be inside amblygonite-bearing units. The distribution of petalite is not so well known, but it, like spodumene, is a lithium-aluminum silicate and presumably it forms in the same part of the sequence. Lepidolite and other lithium micas tend to form in the centers of pegmatites.

Spodumene deposits. --Spodumene deposits of greatest commercial importance are in units containing assemblages 5, 6, and 7. In some pegmatites the spodumene-bearing units are surrounded by barren wall and intermediate zones many feet in thickness. Most commercial spodumene, however, has been produced from a common and rather characteristic type of pegmatite in which the spodumene-bearing units extend to within a few inches or feet of the pegmatite contact.

Many deposits in the Black Hills, S. Dak., are in multiple intrusives. In places the individual pegmatites in these intrusives are separated by a schist parting; elsewhere, outer zones of adjacent pegmatites are in contact with each other. As a result, the entire deposit consists of successive spodumene-rich units separated by barren units. (For example, see Page and others, 1953, pls. 14 and 15.) L. R. Page (oral communication) has observed similar relationships in the Tin-Spodumene Belt of the Carolinas.

The spodumene deposit in the Giant-Volney pegmatite, Tinton, S. Dak., is a large replacement unit (Page and others, 1953, p. 204). Elsewhere, however, known fracture-filling and replacement deposits are small and commercially unimportant.

Spodumene-bearing units large enough to be mined contain a maximum of about 30 percent spodumene or 2.0 percent  $\text{Li}_2\text{O}$ . A content of about 20 percent spodumene is more general. If the spodumene contains 7.5 percent  $\text{Li}_2\text{O}$ , the grade of such a deposit is 1.5 percent  $\text{Li}_2\text{O}$ . In places, however, alteration of the spodumene reduces the grade to as low as 0.1 percent  $\text{Li}_2\text{O}$ .

Altered spodumene has been observed in four structural positions in Black Hills pegmatites: (1) in the deeper and narrower parts of the spodumene-bearing zones; (2) in the outer parts of spodumene-bearing pegmatite in zones rich in feldspar; (3) in the ends of spodumene crystals extending into a quartz core; and (4) along fractures in the pegmatite (Page and others, 1953, p. 56). The lithium content of spodumene-bearing pegmatites may decrease with depth in other districts.

Prior to World War II the only spodumene mining was in deposits containing spodumene crystals large enough for hand-sorting. Ordinarily crystals at least 1 foot in length were required. The development of milling processes, however, has eliminated the requirement for coarse grain size.

Amblygonite deposits. --Amblygonite has been mined chiefly from quartz-perthite-amblygonite or quartz-perthite-amblygonite-spodumene pegmatite in assemblage 5 of the general sequence, but amblygonite has also been obtained from quartz-plagioclase-muscovite pegmatite of assemblage 1 (table 3). In Southwest Africa amblygonite occurs in perthite-bearing units of zone 3 (Cameron, E. N., oral communication). Few deposits contain as much as 10 percent amblygonite, but many deposits contain other marketable minerals that allow the amblygonite to be obtained as a byproduct. Amblygonite deposits, in general, are smaller and lower grade than spodumene deposits.

Amblygonite crystals range in size from grains a fraction of an inch long to masses weighing several hundred tons. The large size of crystals in some deposits makes it possible to produce a very pure concentrate by hand-sorting.

Deposits of lepidolite and other lithium micas. --Lepidolite containing more than 2.5 percent  $\text{Li}_2\text{O}$  has been mined chiefly from lepidolite-albite-quartz pegmatite of zone 8 (table 3); lepidolite also occurs in the spodumene and amblygonite units of some pegmatites. A part of the lepidolite deposit in the Pidlite pegmatite, Mora County, N. Mex., is a replacement unit (Jahns, 1953, p. 1087-1089). Gray lithium micas, containing less than the 2.5 percent  $\text{Li}_2\text{O}$ , occur with microcline, albite, and quartz in zone 11 of the general sequence and also in replacement bodies of the same mineral composition at the Hugo pegmatite, Keystone, S. Dak. (Norton and Page, in preparation). Lepidolite deposits are relatively rare; there are only five pegmatites in North America that have a recorded production of more than 100 tons of lepidolite.

Deposits of other lithium minerals of pegmatites. --Triphylite-lithiophilite and associated iron-manganese phosphates are significant constituents of perthite-bearing units of assemblages 3 and 4, and possibly assemblage 5, of the general sequence (table 3). Triphylite-lithiophilite has never been

commercially important as a lithium source, and consequently virtually no information regarding grade of typical deposits is available. These minerals are intimately intergrown with non-lithium minerals, and the aggregates are stained with phosphates and oxides. Consequently, estimates of the content of lithium minerals cannot be made readily. Assay data are needed.

The only other important lithium mineral is petalite, but no significant deposit has been found in North America.

#### Lithium in brines and saline deposits

The brines at Searles Lake, Calif., are the only commercially important non-pegmatite deposits of lithium. Even in these brines the content of lithium is only about 70 parts per million, corresponding to about 0.015 percent  $\text{Li}_2\text{O}$ . Thus, the grade of this deposit is very nearly the same as the average content of the earth's crust. Other saline deposits in the Mohave desert may also contain lithium, but there are no published data.

A few U. S. Geological Survey analyses have shown that other brines and saline deposits contain small amounts of lithium, but their commercial potentialities have been virtually unexplored. The lithium of evaporites may be large in associated clay minerals. J. J. Fahey (personal communication) found that parts of the Green River formation of Wyoming contain about 0.01 percent  $\text{Li}_2\text{O}$ . Analyses of two potassium-rich parts of a core from the Carlsbad area, N. Mex., by K. J. Murata show the lithium content to be approximately 0.003 percent. Six other samples of potash ore from this area analyzed by R. S. Harner has 0.0001 to 0.0017 percent  $\text{Li}_2\text{O}$ . Old analyses of waters from closed basins, mineral springs, and wells contain lithium (Clarke, 1924, p. 157-162, 185-200). Possibly some lithium-bearing waters are partly of juvenile origin. At Manitou Springs and Steamboat Springs, Colo., 19 analyses by P. R. Barnett of waters collected by E. P. Beroni indicate an average content of 2 parts per million  $\text{Li}_2\text{O}$ . One sample from the Steamboat Springs area had 6.5 parts per million  $\text{Li}_2\text{O}$ , and the solids had 0.11 percent  $\text{Li}_2\text{O}$ .

Lindgren (1933, p. 44-45) has pointed out that salts in many of the chloride ground waters may have been derived from saline deposits. Clarke (1924, p. 187-188) gives two analyses of chloride waters from Saratoga Springs which contain 0.08 and 0.16 percent lithium and an analysis of water from a deep well at Conneautville, Pa., which contains 0.04 percent lithium. These are old analyses and may be inaccurate. Nevertheless, it is clear that saline deposits may contain significant quantities of lithium.

### Lithium in sedimentary rocks

No lithium has been mined from sedimentary deposits, and only hectorite clay is known to contain enough lithium to compare with pegmatites. Nevertheless, other deposits in sedimentary rocks may be found.

The only recorded hectorite deposit is in the Mohave desert near Hector, San Bernardino County, Calif. The hectorite forms bentonite beds in an intensely folded and sheared sequence of Tertiary ash, clay, and limestone (Kerr and Kulp, 1949, p. 74-76). A basalt flow overlies these rocks unconformably. Analyses of the mineral hectorite have shown a content of 1 percent  $\text{Li}_2\text{O}$  (Ross and Hendricks, 1945, p. 27, 35), but no information on the average grade of the deposit is available.

A Tertiary clay 16 miles northeast of Amboy, Calif., has been found to have 0.50 percent  $\text{Li}_2\text{O}$  (Foshag and Woodford, 1936, table 1, p. 241). It is possible that other clays have an appreciable lithium content that has previously been overlooked.

## LITHIUM RESERVES AND RESOURCES

### Determination of grade and reserves

The grade and reserves of deposits of lithium minerals and of other minerals in pegmatites can be estimated with reasonable accuracy (Norton and Page \_\_/). Large samples must be used to determine the

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\_\_/ Norton, J. J., and Page, L. R., Methods used to determine grade and reserves of pegmatites, in preparation.

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grade of coarse-grained lithium-bearing units in pegmatites, but otherwise there are no special sampling problems in collecting material for analysis.

Difficulties have been experienced in obtaining accurate analyses with the gravimetric and volumetric techniques used by commercial analysts. Table 4 shows the wide range of results obtained on three samples analyzed by seven reputable laboratories in 1944.

Table 4. --Comparative analyses of three spodumene samples,  
Edison mine, Keystone, S. Dak. 1/

Selected as having	Lithia content, in percent						
	U. S. Bur. Mines	Analyst A	Analyst B	Analyst C	Analyst D	Analyst E	Analyst F
Low lithia content	0.79	0.94	Trace	1.10	1.24	1.38	1.48
Medium lithia content	2.80	3.12	2.88	3.50	3.50	3.52	3.55
High lithia content	4.63	5.54	3.10 5.54 5.50	6.05	6.00	5.41	5.74

1/ After Clarke, F. F., and others, 1948, p. 22, table 7.

More recently the flame photometer has been widely used for lithium analyses. The Lithium Corporation of America has found that analyses of spodumene-bearing samples by flame photometer are consistently higher than results from a routine chemical technique also used by this company. One explanation is that the chemical method extracts all the lithium in spodumene, but not all the lithium in associated minerals (Clarke, F. F., oral communication).

Many deposits have more than one mineral containing lithium. Usually, however, lithium is extracted from only one of these minerals, and the others are waste products. Consequently, chemical analyses are not completely adequate for grade determinations unless the deposit contains only one lithium mineral, or the proportions of the various lithium minerals in the deposit are known. In order to correct

for errors that may be introduced in this way, grade has sometimes been determined by measuring the intercepts of lithium minerals on equally spaced lines along exposed surfaces. Grain counts under the microscope have also been used (Gries, 1950, p. 6). The most accurate results can be obtained by screening the samples, making grain counts for each sieve size, and computing weighted averages. Such an elaborate procedure may not always be necessary. At least one investigation of the spodumene content of analyzed samples appears to have been successful without the precaution of sieving the samples (Gries, 1950, p. 6). Nevertheless, spodumene has such a great tendency to break to small sizes that grain counts used alone may give erroneously high results.

Spodumene and amblygonite have a greater specific gravity than the other essential minerals of most deposits. Consequently, heavy liquid separations can be used for approximate determinations of grade. Heavy accessory minerals may, however, cause significant inaccuracies.

Reserves in zones or other pegmatite units can be determined by projections along strike, dip, and plunge. The techniques used for this purpose in pegmatites are essentially the same as for other mineral deposits. Detailed discussion of these methods is being presented elsewhere (Norton and Page, in preparation).

#### United States

Lithium reserve data compiled in table 5 show that pegmatites in the United States contain indicated reserves of 5,000,000 units and inferred reserves of approximately 124,000,000 units of lithia. Searles Lake, Calif., may contain 9,000,000 units of lithia that can be extracted by the methods now in use. In the mining and concentrating techniques now used at lithium mines, a significant proportion of all lithium minerals--perhaps as much as one-third--are not recovered. Even with such losses, however, this reserve would last many hundreds of years at the 1952 production rate of 109,000 units annually.

Nearly all of the lithium reserves of pegmatites are in spodumene. The Black Hills district, S. Dak., has significant amblygonite reserves, but these contain not more than a few hundred thousand units of  $\text{Li}_2\text{O}$ . Lepidolite reserves are trivial in comparison with spodumene and amblygonite.

Table 5. --Lithium reserves of the United States <sup>1/</sup>

Localities	Principal lithium mineral	Other lithium minerals	Indicated reserves			Inferred reserves			Total units $\text{Li}_2\text{O}$
			Average depth in feet	Average grade percent $\text{Li}_2\text{O}$	Units $\text{Li}_2\text{O}$	Average depth in feet	Average grade percent $\text{Li}_2\text{O}$	Units $\text{Li}_2\text{O}$	
Tin-Spodumene belt, North and South Carolina	Spodumene	Amblygonite	400	1.7	4,000,000	450	1.3	124,000,000	128,000,000
Black Hills, South Dakota	Spodumene	Amblygonite, lepidolite	100	1.2	1,200,000	100	1.2	400,000	1,600,000
Pegmatite districts of New England, Colorado, Arizona, New Mexico, California, and Wyoming	Spodumene	Amblygonite, lepidolite		1.2	200,000				200,000
Upper deposit at Searles Lake, California	Brine		90	0.015	9,000,000				9,000,000
Totals (rounded)					14,000,000			124,000,000	140,000,000

<sup>1/</sup> The cutoff grade used for pegmatite deposits is 1.0 percent  $\text{Li}_2\text{O}$ .

The cut-off grade used for pegmatite deposits in table 5 is 1.0 percent  $\text{Li}_2\text{O}$ . If deposits containing between 0.4 and 1.0 percent lithia were also included, the reserves in all districts would be increased somewhat, but the change in the Carolina reserves would be small. Inasmuch as the Carolina reserves are such a very large proportion of the national total, the overall effect of decreasing the grade to 0.4 percent  $\text{Li}_2\text{O}$  would be slight.

Most of the reserves in table 5 are within 300 feet of the surface, but calculations for a few of the larger deposits have been extended to depths as great as 800 feet.

Doubtless lithium deposits could be found at much greater depths, but reserves near the surface are so great that with few exceptions anything below 300 feet must be considered submarginal at the present time.

Additional lithium resources are in types of deposits not being worked at present, and are not included as reserves in table 5. The lithium clay at Hector, Calif., is an example. No saline deposits have been included except the upper salt body at Searles Lake, Calif.

#### North and South Carolina

A very large share of the known spodumene reserves of the United States are in the Tin-Spodumene belt at the border of North and South Carolina near Kings Mountain, N. C. (fig. 1). This district has recently been studied in detail by W. R. Griffitts of the U. S. Geological Survey (1954), and he has supplied the reserve data used in this report (written communication). An earlier study was made by T. L. Kesler (1942).

The Tin-Spodumene belt contains many hundreds of lenticular, tabular, and irregularly shaped pegmatites intrusive into gneiss and schist, and more rarely into quartz monzonite. Spodumene is a major constituent of many of these pegmatites, and amblygonite has been recognized as an accessory mineral. Lithium deposits extend from wall to wall of many of the pegmatites. Some of these deposits are very large: one is 3,200 feet long, and another is 225 feet thick. Many other deposits, on the other hand, are so small that only very small-scale mining operations will be feasible.

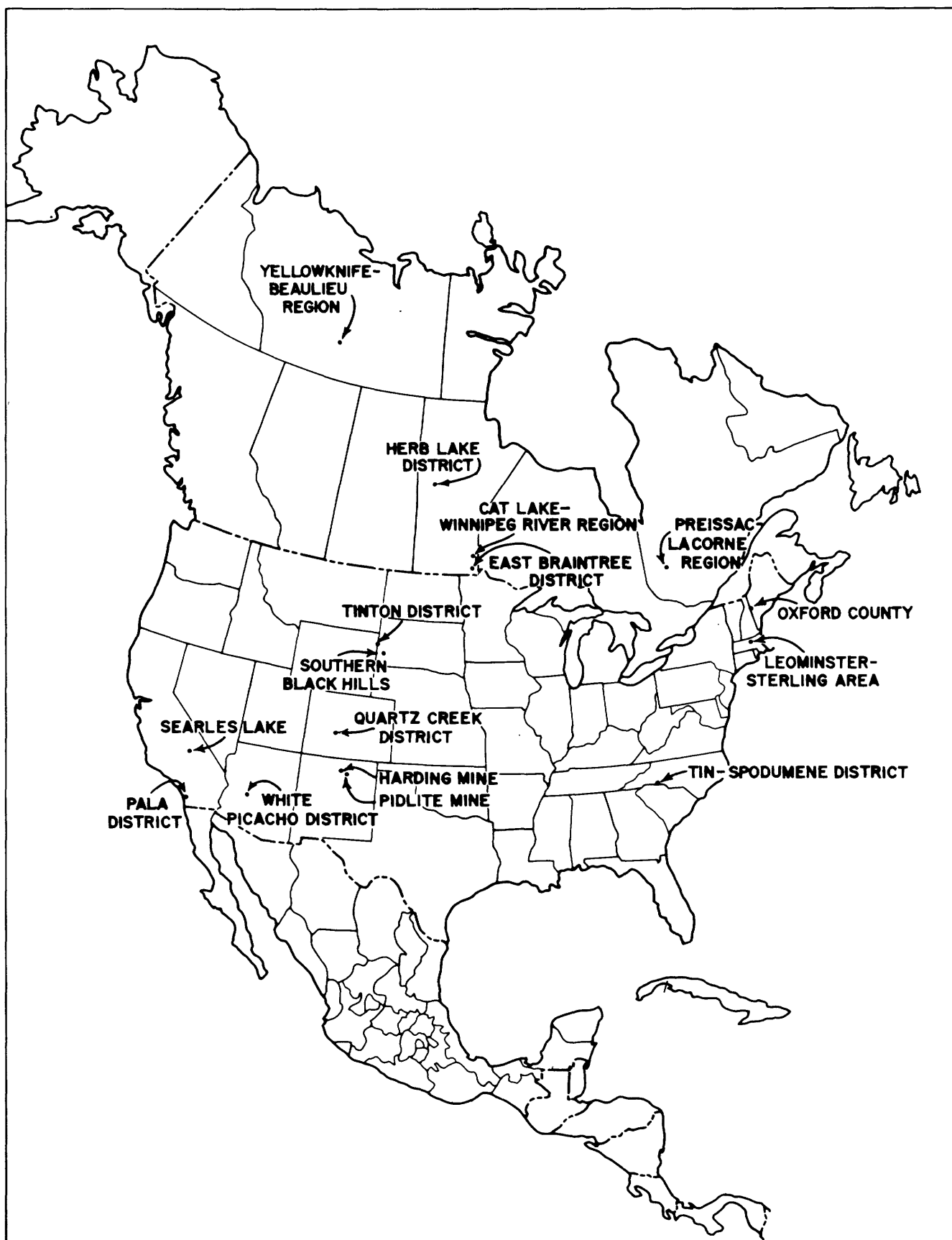


FIGURE 1. INDEX MAP SHOWING THE PRINCIPAL LITHIUM LOCALITIES OF NORTH AMERICA

Analyses and estimates of the spodumene content of many exposures have been used to determine grade of these deposits. The average grade of spodumene-bearing pegmatite (table 5) is 1.7 percent  $\text{Li}_2\text{O}$ .

Reserves of some deposits have been determined by drilling. Reserves of others have been estimated by projections from the surface to a depth of 300 feet. Many deposits exposed at the surface will, of course, lens out at shallow depths, but deposits not reaching the surface should compensate for them.

Lepidolite has been recognized in Franklin County, N. C., but reserves are not known to be significant (Griffitts, 1953, p. 284).

### South Dakota

Lithium deposits have been found in the Tinton district of the northern Black Hills and in three districts in the southern Black Hills, S. Dak.: (1) the Keystone district, northeast of Harney Peak; (2) the Hill City district, northwest of Harney Peak; and (3) the Custer district, southwest of Harney Peak. The principal known deposits are as follows: Tinton district--Giant-Volney; Keystone district--Etta, Edison, Hugo, Bob Ingersoll Nos. 1 and 2, and Dyke Lode; Hill City district--Mateen; and Custer district--Beecher Lode, Beecher No. 2, and Tin Mountain. Only five of these deposits are known to contain more than 100,000 units of  $\text{Li}_2\text{O}$ . Lithium minerals have been found in approximately 40 additional pegmatites.

Spodumene is the dominant lithium mineral in nearly all deposits, and constitutes 85 percent of the known reserves. Amblygonite is the chief lithium mineral at the Hugo mine, and ranks close to spodumene in the Beecher Lode. Lepidolite is the only lithium product of the Bob Ingersoll No. 1 pegmatite. Known lepidolite reserves in the Black Hills are small, but potentialities have by no means been exhausted.

A significant proportion of the lithium reserves at the Etta, Tin Mountain, Beecher Lode, and Hugo can be recovered by hand-cobbing. Milling is necessary for most of the rest of the Black Hills lithium deposits.

## California

Searles Lake-Mohave area, --The principal source of the sodium and potassium salts and also by-product lithium at Searles Lake, San Bernardino County, Calif., has been brine that fills interstices in a salt body reaching a maximum depth of about 90 feet. A second salt body occurs at a still greater depth. The Searles Lake deposits have been described in various reports (Gale, 1945; Dyer, 1950; Ryan, 1951).

Available published data are adequate only for making an approximate estimate of reserves of lithium obtainable by present methods at Searles Lake. The brine containing lithium probably can be pumped from an area of at least 20 square miles. The average thickness of the upper salt body is probably between 40 and 70 feet. The brine occupies a volume of between 25 and 50 percent of the salt body. Data by Mumford (1949, p. 513) and Gale (1945, p. 442-446) indicate that the grade is about 0.01 percent  $\text{Li}_2\text{O}$ ; more recently Ryan (1951, table 1, p. 449) has given the grade as 0.015 percent  $\text{Li}_2\text{O}$ . The specific gravity of the brine is 1.30 (Dyer, 1950, p. 41). Calculations based on these figures indicate that the brine contains between 2,000,000 and 12,000,000 units of lithia. These calculations do not allow for transfers of lithium during reactions between the crystalline salts and the brine.

Another approach to the problem of estimating reserves may be made by use of Dyer's estimate (1950, p. 44) that 35,000,000 tons of sodium and potassium salts can be recovered by methods now in use. Data presented by Ryan (1951, p. 452) indicate an approximate recovery of 1 part lithia for every 400 parts of sodium and potassium salts obtained. By applying this ratio to Dyer's estimate, the reserves of lithia are found to be 9,000,000 units. This is the figure used in table 5.

Ryan (1951, p. 449) states that brine in the lower salt body has 0.006 percent  $\text{Li}_2\text{O}$ . Presumably, the evaporite beds also contain lithium. If lithium is ever recoverable from these sources, the reserves may be increased by tens of millions of units.

Clay at Hector, Calif., and possibly clays, salines, and other deposits elsewhere in the Mohave area contain lithium, but no resource data are available.

Pala pegmatite district. --California also has lithium pegmatites in the Pala district, San Diego County.

The Stewart pegmatite was at one time a significant source of lepidolite, and amblygonite was also produced. Production since 1928 has been meager, and evidently no substantial reserves are known (Jahns and Wright, 1951, p. 52-55).

#### Arizona, New Mexico, Colorado, Wyoming, and New England

Small lithium reserves in pegmatites are known in Arizona and New Mexico, and a few deposits are in Colorado, Wyoming, and New England.

Jahns (1952) estimates reserves of at least 8,000 tons of spodumene and amblygonite in the White-Picacho district near Wickenburg, Ariz.

In New Mexico, the Harding mine in Taos County has long been known for lepidolite and spodumene, and the Pidlite mine in Mora County has been a source of lepidolite. Another important lepidolite source has been the Brown Derby mine in the Quartz Creek district, Gunnison County, Colo. (Staatz and Trites, 1954, in press). Amblygonite and spodumene also occur in Colorado, but no substantial reserves of lithium are known in the state (Hanley and others, 1950, p. 14). Wyoming has pegmatites containing petalite, lepidolite, spodumene, and probably amblygonite, but no significant deposits have been reported.

Lithium minerals have been recognized in Maine, Massachusetts, and Connecticut (Cameron and others, 1954; Billings and Wolfe, 1943). Reserves are small.

#### CANADA

Canada has large reserves of spodumene and small reserves of other lithium minerals. R. B. Rowe, of the Geological Survey of Canada, has compiled data on Canadian deposits, and part of the results have been published (Rowe, 1953a and b).

The Cat Lake-Winnipeg River region of southeastern Manitoba probably has at least 2,000,000 units of lithia (Page, L. R., oral communication).

Three lithium-bearing pegmatites in the Preissac-LaCorne region, north of Val d'Or, Quebec, have been described by Derry (1950) and Rowe (1953b). These deposits contain reserves of at least a few hundred thousand units of lithia.

Spodumene and other lithium minerals are also known in the East Braintree and Herb Lake districts of Manitoba and in the Yellowknife-Beaulieu region of the Northwest Territories (Rowe, 1953a, and Jolliffe, 1944).

#### FUTURE OF THE LITHIUM MINING INDUSTRY

The lithium mining industry has expanded about eight-fold in the period from 1947 through 1953. It is generally anticipated that the demand for lithium will continue to expand, perhaps even to 50 or 100 percent above the 1953 level within a few years. Reserve figures indicate that even greater expansion is possible without significant change in mining and milling methods or costs.

Spodumene is so much more abundant than the other lithium minerals that it will continue to be the chief raw material. Lepidolite mining in North America is not likely to be important unless new deposits are discovered, but lepidolite will doubtless be imported. Searles Lake, Calif., will continue to be a significant source of lithium. Possibly at some future time other saline deposits or sedimentary rocks may also become lithium sources.

Flotation milling for spodumene, as at Kings Mountain, N. C., and in the Black Hills, S. Dak., is firmly established in the industry. Nevertheless, a few deposits containing cobbable spodumene and amblygonite, notably in the Black Hills, will continue to furnish a part of the lithium supply.

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